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Visualization of the microscopic flow profile of state-of-the-art absorption heat pump working pairs under operational conditions

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HIGHLIGHTS

- We successfully used an innovative optical method in a lab-scale falling-film AHP.
- We measured simultaneous film thickness and velocity profiles during operation.
- LiBr/water and an additive enhanced LiBr/water solution were used as working pairs.
- The additive enhanced solution is more often deflected from the main flow direction than the pure one.
- We discussed the main limitations of the method and gave ideas to improve it.

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ABSTRACT

The research and development of novel working pairs and highly efficient heat exchangers for absorption heat pump applications require a detailed analysis of the microscopic flow profile at the absorber heat exchanger during the absorption process. A recently developed Single Aperture Defocussing Micro Particle Tracking method, based on a conventional Particle Image Velocimetry system, demonstrates the possibility of simultaneous measurements of velocity profiles and film thicknesses in falling film absorbers at steady-state flows. We show first results of velocity profile measurements of the state-of-the-art working pair LiBr/water, with and without a 2-Ethyl-1-Hexanol additive, during operation in a lab-scale absorption heat pump. Based on the results of the measurements, the advantages and disadvantages of the developed measurement technique and their potential application in the characterization of novel working pairs is discussed.

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1. Introduction

Absorption Heat Pumps (AHPs) could help to reduce the electric energy consumptions of chiller and heating applications. Several authors as [4] showed that the main restrictions to the performance of an AHP is given by the ambient conditions (temperature reservoirs), the different heat and mass transfers and the thermodynamics of the working pair. In a real world application, the temperature levels will be given and can not be changed. Choosing the working-pair according to the temperature levels is restricted to little options. The most common used working pairs are water/ammonia for evaporator temperatures below 0 °C and LiBr/water for temperatures above 0 °C.

An obvious way of improving the performance of an AHP, is by enhancing the heat and mass transfer at the heat exchangers. This is done by clever designs what could finally result in lower investment costs. From an AHP designer point of view, the heat exchanger can be modified by changing the principal absorber design (horizontal tube, falling film, etc.), the geometry (length, thickness, surface condition, etc.) or the material (stainless steel, cooper, etc.). Hence, detailed and experimentally verified models of the interaction between the absorbing solution and the mechanical structures are necessary to predict an optimal design.

The review paper from Ref. [6] lists different models for falling film absorbers which were developed until 2001. Depending on the model, the influence of the film Reynolds number on the absorption process differs from each other [2]. investigated the influence of the Reynolds Number on the heat and mass transfer in a horizontal tube absorber. He found a slight influence of the Reynolds number on the heat transfer but no dependency on the mass transfer due to the low variation of the Reynolds number in their experiment.

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Nomenclature

χ	mass fraction (−)
$\dot{m}$	mass flow rate (kg s^{-1})
$\dot{Q}$	heat transfer rate (W m^{-2})
$\dot{V}$	volume flow rate (m^3 s^{-1})
ϕ	angle (°)
ϱ	density (kg m^{-3})
c_p	specific heat capacity (J kg^{-1} K^{-1})
m	mass (kg)
n	refraction index of solution (−)
p	pressure (bar)
T	temperature (°C)
v	velocity (m s^{-1})
x,y,z	cartesian coordinates (m)
2E1-H	2-Ethyl-1-Hexanol
D-μPTV	defocussing micro PTV
AHP	absorption heat pump
E-A	evaporator-absorber
PIV	particle image velocimetry
PTV	particle tracking velocimetry

Subscripts

abs	absorber
amb	ambient
eff	effective
eva	evaporator
in	inlet
opt	optical
out	outlet
sol	solution

Recent theoretical works on non-wavy absorbing falling films went further and proved the existence of an optimum Reynolds number for absorption processes [5]. It is clear that operating an AHP at the optimum Reynolds number is necessary for a highly efficient AHP. Since the Reynolds number of a falling film depends on viscosity, velocity and film thickness, the knowledge of these three parameters is important during operation in an AHP. Both, the velocity and the film thickness can be deduced from velocity profiles whereas the viscosity is determined by the chemical composition of the working pair, the concentration of the working pair and the ambient conditions.

On the one hand, the detailed knowledge of the velocity profiles is therefore important to a designer of an AHP who wants to operate the apparatus at the optimal Reynolds number for a given viscosity. On the other hand, the velocity profiles could also be important to a chemical engineer, who could adapt the viscosity of the working pair to provide the best suited working pair for a given apparatus design. Furthermore, the investigation of local velocity profiles in novel working pairs could help to understand and may be predict the flow profile of such systems and their interaction (heat transfer) with the structure.

A further possibility of enhancing the absorption performance by chemical ways is by adding additives, like 2-Ethyl-1-Hexanol (2E1H) to the state-of-the-art working pair LiBr/water. Due to Marangoni convection, caused by the change of the dependency of the surface tension from the concentration compared to pure LiBr/water, instabilities increase and lead to local thinning of the film and increased turbulences [14]. Highly sophisticated models are needed to describe the phenomena caused by Marangoni convection inside an absorbing film in detail. The velocity profiles could be necessary input parameters to such models. Since, these phenomena only appear during absorption conditions, a closed system like the one proposed in this work has to be used to study these effects.

But which technique is the best suited to measure the flow profiles during operational conditions in an AHP?

Several electric (needle-contact, electrical-conductance) and optical, non-intrusive methods like Light Absorption, Light Reflection, Laser Induced Fluorescence (LIF), Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV), exist to measure film thicknesses and/or velocities. From all these methods, a Single Aperture Defocussing Micro Particle Tracking method seems to be the best suited application to perform such a task in an AHP during operation. First of all, an optical method gets along without the need of contact or an applied current. Since, many of the solutions used in absorption technology have an ionic character, applied currents could lead to chemical precipitates at the contact probes. Secondly, reflection and refraction effects of the moving fluid can be neglected with an orthogonal view as is used in a single camera system. The easier handling of a single camera system compared to a multiple camera system is evident. If PTV methods are used, micro particles of nearly the same density as the fluid would be added to the solution. Assuming that the particles have the same velocity as the fluid, one can measure the fluid flow by tracking these particles.

As proposed by Ref. [12] and pointed out in further detail by Ref. [9]; the spherical aberration of a microscope lens can be used to obtain particle movements, not only in the focal plane but furthermore in parallel planes in front and behind of the focal plane, as well. A sophisticated algorithm is needed to detect and track the particles in such an arrangement. Lately [11], demonstrated some major improvements to the algorithms used by Ref. [9] in order to increase the accuracy of the evaluation method and to decrease the evaluation time in such a set-up.

Note that [9] introduced their work as a new μPIV technique. In principle, we use similar optical arrangements as Paschke et al. However, besides the fact that we carry out our experiments under nearly vacuum conditions, we furthermore use different evaluation algorithms as pointed out in Ref. [11]. According to [10] and [1]; the tracking of individual particles followed by a suitable particle pairing algorithm is commonly referred to as Particle Tracking Velocimetry (PTV) whereas Particle Image Velocimetry (PIV) refers to cross-correlation-based algorithms using multiple particles. Since we track single particles in our work, we suggest the name Defocussing Micro Particle Tracking Velocimetry (D-μPTV) as an umbrella term for the used technique and evaluation algorithms.

Because of the need of many particles, in order to minimize the statistical errors, a steady-state flow is required for the proposed technique. Hence, time dependent instabilities could not be observed directly. Nevertheless, instabilities in the working pair can be measured indirectly by statistical methods as we will show later.

Although this work focuses on absorption processes, the proposed method is also suitable to verify calculations of velocity profiles of different kinds of one and two-phase flow regimes. Furthermore, it could be an alternative to μPIV measurements in microgrooves of heat sinks as were used in Ref. [13] or could supplement μPIV measurements of plate heat exchangers, as performed by Refs. [8]; with a depth information.

However, in the following, the D-μPTV measurement method will be introduced into the field of absorption and first results will be discussed.

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